ENGINEERING DEVELOPMENT OF COAL-FIRED
HIGH-PERFORMANCE POWER SYSTEMS

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INTRODUCTION

Foster Wheeler Development Corporation is leading a team of companies in the development of a High-Performance Power System (HIPPS). This work is being sponsored by the U.S. Department of Energy as part of their "Combustion 2000" program. The other members of the team are Bechtel, Foster Wheeler Energy Corporation and the University of Tennessee Space Institute (UTSI). HIPPS is a coal-fired combined cycle system that is capable of efficiencies greater than 47 percent (HHV). Our HIPPS concept is based on the partial gasification of coal which provides fuel gas for a gas turbine and char for an atmospheric boiler/air heater.

A schematic diagram of the base case commercial plant design is shown in Figure 1. A pressurized, air blown, fluidized bed pyrolyzer converts the coal into fuel gas and char. The char is fired in a high temperature advanced furnace (HITAF) which heats both air for the gas turbine and steam for a steam turbine. The HITAF is an atmospheric, pulverized fuel-fired, boiler/air heater The gas turbine air is heated to 760 $^{\circ}$C (1400 $^{\circ}$F) in the HITAF. This temperature can be achieved with tube banks constructed of alloy steel. The air from the HITAF is then heated to a gas turbine inlet temperature of 1288 $^{\circ}$C (2350 $^{\circ}$F) in a topping combustor that is fired with fuel gas from the pyrolyzer. The gas turbine exhaust is divided into two streams. One stream is used as combustion air in the HITAF and the other goes through a Heat Recovery Steam Generator (HRSG).

An alternative arrangement of HIPPS uses a ceramic air heater to obtain higher exit air temperatures from the HITAF. With this concept, the air leaves the alloy tube banks at 760 $^{\circ}$C (1400 $^{\circ}$F) and then goes to a ceramic air heater where it is heated to 982 $^{\circ}$C (1800 $^{\circ}$F) or greater. The pyrolyzer is operated at relatively low pressures in this HIPPS arrangement, and the fuel gas is fired in a furnace upstream of the ceramic air heater. Heating of the air beyond the air heater outlet temperature is accomplished by topping combustion with natural gas.

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There is also a repowering arrangement of HIPPS. This concept is shown in Figure 2. Here the key elements of the HIPPS technology, generation of fuel gas and combustion of char, are applied to an existing boiler. The pyrolyzer subsystem is the same as in the base case arrangement, and the fuel gas is fired directly in the gas turbine. The gas turbine exhaust is used as combustion air in the boiler in a "hot windbox" type of arrangement. When the gas turbine is sized to match the boiler air requirements, the amount of char generated is insufficient to fully fire the boiler. About 40 percent of the boiler fuel heat input is supplied by raw coal.

A design study was done on a specific 100 MW boiler, and HIPPS repowering was shown to increase the efficiency by 5 percentage points and the capacity by about 20 percent [1]. The boiler modifications were typical of what is required in "hot windbox" repowering. The air heater would be removed and economizer tube banks would be added. Some tube elements in the boiler would also be removed to accommodate the effects of using gas turbine exhaust for combustion air.

APPROACH

The two major subsystems that require development in the HIPPS project are the pyrolyzer and the char combustion subsystems. A combination of computer modeling and pilot plant testing is being used to develop the design tools that will be required to design a commercial plant.

The pyrolyzer is very similar to what is called the "carbonizer" in the Second-Generation PFB system, and that computer model was the starting point for the HIPPS pyrolyzer computer model. Some particle dynamics modeling was added since the particle size distribution (PSD) of the char is of particular importance in HIPPS. Pyrolyzer pilot plant tests are currently being run in our Livingston, New Jersey facility, and the model will be modified based on the results of this testing. The testing in Livingston is at coal input flows of up to 227 kg/h (500 lb/h). After this testing is completed, a larger scale pyrolyzer with coal input of about 2730 kg/h (6000 lb/h) will be tested, and the computer model will be modified again if necessary.

A key requirement of HIPPS is that the char that is generated in the pyrolyzer can be efficiently fired in pulverized fuel burners with gas turbine exhaust as the combustion air. This impacts both the design of the pyrolyzer and the HITAF burners and furnace. The pyrolyzer must generate char of acceptable PSD and the burner/furnace system must be capable of operation with this low volatile fuel and low oxygen combustion air.

The char combustion is being investigated with three methods; laboratory analysis, computer modeling and pilot plant testing. Standard laboratory tests for solid fuel analysis

are being performed on char from pyrolyzer pilot plant tests. In this manner, the combustion characteristics of the char can be compared with fuels for which there is experience at commercial scale. Computer modeling of the combustion is also being done, and pilot plant testing will be used to benchmark the computer modeling.

The PCGC3 combustion computer model is being used to model the HITAF furnace. This model was developed by Brigham Young University, but it has been modified by FWDC for our applications. The furnace at the Foster Wheeler Combustion and Environmental Test Facility (CETF) has been modeled with HIPPS conditions [2]. Char combustion tests will be run at this facility. Design and process parameters have been varied in the computer modeling to assist in the design modification decisions and the development of a test matrix. The CETF is being modified for arch-firing, and systems are being added to provide heated, low oxygen air for combustion.

RESULTS

PYROLYZER TESTING

Figure 3 is a schematic diagram of the pyrolyzer pilot plant in Livingston, New Jersey. The pyrolyzer is currently in a jetting fluidized bed arrangement which is a type of bubbling bed. Tests are being run with different coal and sorbent size distributions. Sand is also used in some tests to investigate operation with an inert bed. Bed temperature and steam injection rate are additional parameters that are being varied in the test program.

Coal and sorbent are pressurized in a lock hopper system and fed pneumatically to the pyrolyzer. Additional air and in some cases steam is also fed to the pyrolyzer. During operation, the total air flow rate is adjusted to maintain the desired bed temperature at the set coal and steam flow rates. The air flow is always kept well below stoichiometry so that fuel gas and char are produced. Fuel gas and eluitriated solids leave the top of the pyrolyzer. There is a bottom solids drain in the pyrolyzer, but the objective of HIPPS pyrolyzer operation is to have as much of the char as possible leave the top of the pyrolyzer with a PSD suitable for pulverized fuel combustion.

The char and any sorbent particles that carryover from the pyrolyzer are separated from the fuel gas in the barrier filter. In the commercial HIPPS plant, the fuel gas and entrained solids would be cooled to 538 $^{\circ}$C (1000 $^{\circ}$F) before the barrier filter. At this point, there is no equipment in the pilot plant to cool this stream before the barrier filter. The solids separated in the barrier filter are cooled and then depressurized in a lock hopper system. Figure 3 shows the configuration in the initial tests where the char goes directly into drums for storage. The plant is being modified to include dense phase transport of the char through 60 feet of pipe to a baghouse. This transport will simulate the transport of the char to the combustion system.

The fuel gas is analyzed in real time with a mass spectrometer. It is then depressurized with an orifice, and quenched. After the quench, a bag sample is taken for laboratory analysis. A baghouse and incinerator then prepare the gas for discharge to the atmosphere.

Table 1 shows some of the test conditions achieved so far. At the time of this writing, the pyrolyzer has been operated with two types of bed materials; coarse sorbent with coarse sand and coarse sorbent alone. In all the tests, the coal feed was pulverized. Initial problems feeding the pulverized coal limited the coal feed rate, but the feed system has been modified to achieve coal flow rates of up to 227 kg/h (500 lb/h).

The objective of the pilot plant testing is to obtain the data necessary to develop a computer model for pyrolyzer operation under HIPPS conditions. Our existing computer model is being compared with the pyrolyzer pilot plant test results to determine if modifications are necessary. Table 2 shows comparisons between test results and model predictions for some of the test points. A fairly good agreement is seen in general. The model does seem to be predicting higher methane yields than we are experiencing, and some adjustments may be made to the program as we get more data. Also, the model currently converts all the fuel nitrogen to NO_x which is an overly conservative assumption.

The data in Table 2 is from the pilot plant, and the computer model inputs correspond to these conditions. As the scale of pyrolyzer is increased, the proportion of heat loss and nitrogen injection will decrease. These conditions will affect the outputs, but they are built into the model, and the model will be benchmarked at each scale of pilot plant testing.

The char particle size obtained from the pyrolyzer is of great concern as it must be in the proper range for effective combustion in a pulverized fuel-fired furnace. Figure 4 shows the range of char PSD's from samples taken during one of the test runs. Also shown in this figure are the particle size distributions that have been used in the computer modeling of the HIPPS furnaces at the CETF and at UTSI. The size distributions modeled gave good carbon burnout which indicates that the char PSD's generated in the pilot plant will be acceptable. The pilot plant char PSD is close to that assumed in the modeling and has lower amounts of the larger particles. It is the larger particles that tend to produce unburned carbon so the pilot plant char should have better burnout potential.

CHAR CHARACTERIZATION

A series of characterization tests were done on the Pittsburgh #8 char obtained during pilot plant testing of the Second Generation PFB under similar conditions (air to fuel ratio and temperature) as the HIPPS runs. Now that char is available from the HIPPS pyrolyzer testing, these tests will be repeated. It is not anticipated that the general results or conclusions will change since the char used from the Second-Generation PFB tests was generated under similar conditions and taken from the stream that was elutriated from the bed.

Table 3 describes the reactivity tests which were performed on the Pittsburgh #8 char as well as other low volatile fuels for comparison. The other selected coals were two anthracites and a low volatile bituminous coal. The T_{15} reactivity test was performed to give an indication of fuel ignition potential. Thermogravimetric analysis (TGA) was performed for qualitative comparison of the different fuels with respect to their ignition and burnout temperatures, and drop tube tests were conducted to determine burnout characteristics under conditions more representative of utility boilers. The particle residence time in the drop tube furnace was about 2 seconds.

Table 4 shows the reactivity index (T_{15}) and TGA results. Pittsburgh #8 char is seen to be similar to the Anthracite A in reactivity index and TGA ignition temperature, however, the TGA burnout temperature is much lower than all the other low volatile fuels listed (650 ^{o}C versus 790 to 860 ^{o}C). The reason for this good burnout potential is probably the surface area which is significantly higher than the other fuels. The reactivity index of the char is shown to be 429 ^{o}C. Fuels with T_{15} values higher than 275 ^{o}C are traditionally arch-fired in boilers to maintain flame stability.

Table 5 summarizes the drop tube furnace results. Pittsburgh # 8 char was shown to have superior carbon conversion, again, most probably due to its high surface area (163.8 m^2/g of carbon) compared to the other coals (2.0 to 20.6 m^2/g of carbon). Carbon burnout of the Pittsburgh #8 char in the drop tube furnace was 97.4 % at 1500 ^{o}C and 86.3 % at 1400 ^{o}C.

The characterization tests showed excellent combustibility of the char. However, ignition and flame stability may be a potential concern. Current commercial plant conceptual designs assume 10% of the heat input is from raw coal. Ignition and flame stability issues will be investigated in burner testing at the CETF.

CHAR COMBUSTION SYSTEM TESTING

As previously mentioned, the char combustion system will be tested at the Foster Wheeler CETF. This facility has a furnace capable of heat inputs up to 71.1 MJ/h (75 MMBtu/h). It is currently being converted to an arch-firing arrangement for HIPPS testing. The arch-firing concept is shown in Figure 5. This design has been used for anthracite and other low volatile fuels for many years. The burners are fired downward into the furnace and secondary air is added along the path of the flame. This results in a long flame with more control over the quenching effects of the secondary air. Also, there is some reentrainment of the hot gases into the burner zone which helps to stabilize ignition.

Other modifications to the CETF have been designed for HIPPS testing, and we are in the process of procuring the equipment for these modifications. A system is being added to simulate the gas turbine exhaust that is used as combustion air in HIPPS. A combination of flue gas recycle and a duct burner are used to get the temperature and reduced oxygen content that will be typical of the gas turbine exhaust. Other modifications are being made to enable the feeding of char, coal and limestone from silos.

Some char from the Livingston, New Jersey pyrolyzer tests will be fired in the CETF but there will not be sufficient amounts of this char for a comprehensive burner test program. Commercially generated char will be used for most of the CETF testing with final confirmation of the preferred designs done with the HIPPS generated char.

FUTURE ACTIVITIES

Testing of the pyrolyzer pilot plant in Livingston will continue.   Tests will be run under different bed conditions, and a char transport system is being added. We will also be testing a solids flow pump that would take the place of a lock hopper system. The data from the pyrolyzer tests will be used to update the computer model if this is necessary.

Some firing of commercial char will be done at the CETF this fall, but the testing under full HIPPS conditions will not start until early next year when the process equipment is installed.

REFERENCES

1. Shenker, J., et al.,1995, "High Performance Power System Development Including Repowering Options",1995 International Joint Power Generation Conference.
2. Cho,S. M.., et.al., 1997,"Characteristics of Char Combustion in a High Temperature Advance Furnace for the High Performance Power System", Proceedings of the 22nd International Technical Conference on Coal Utilization and Fuel Systems, pg. 233-243.
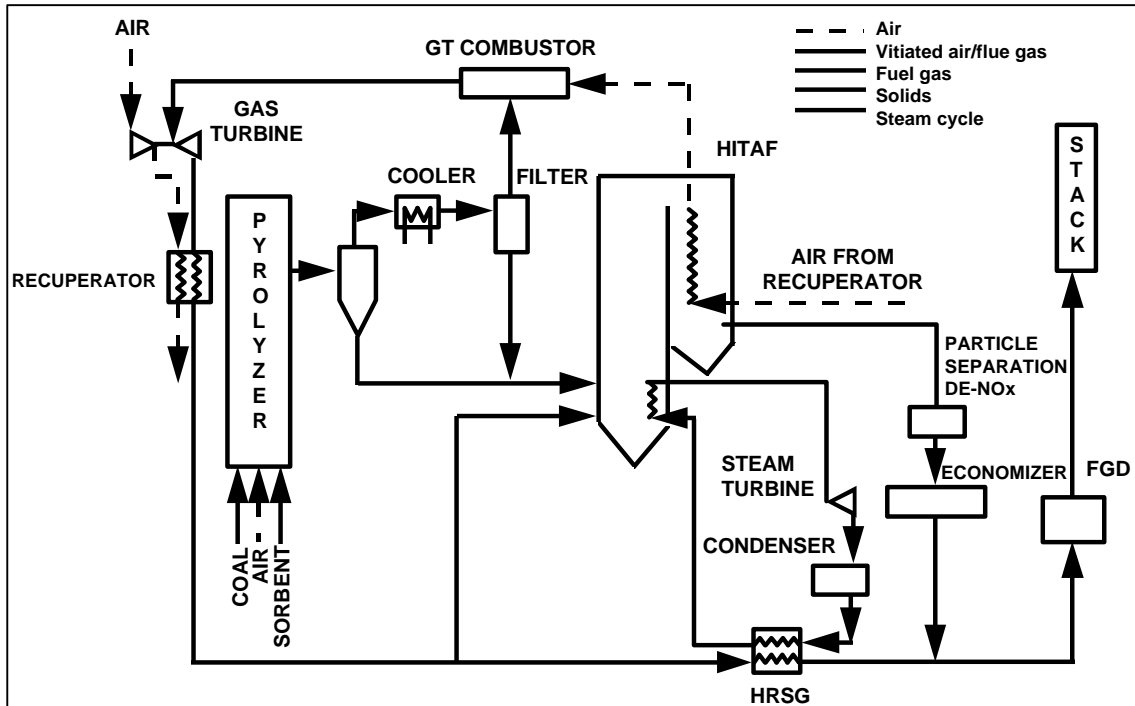
Figure 1. Schematic of the HIPPS Commercial Plant Design
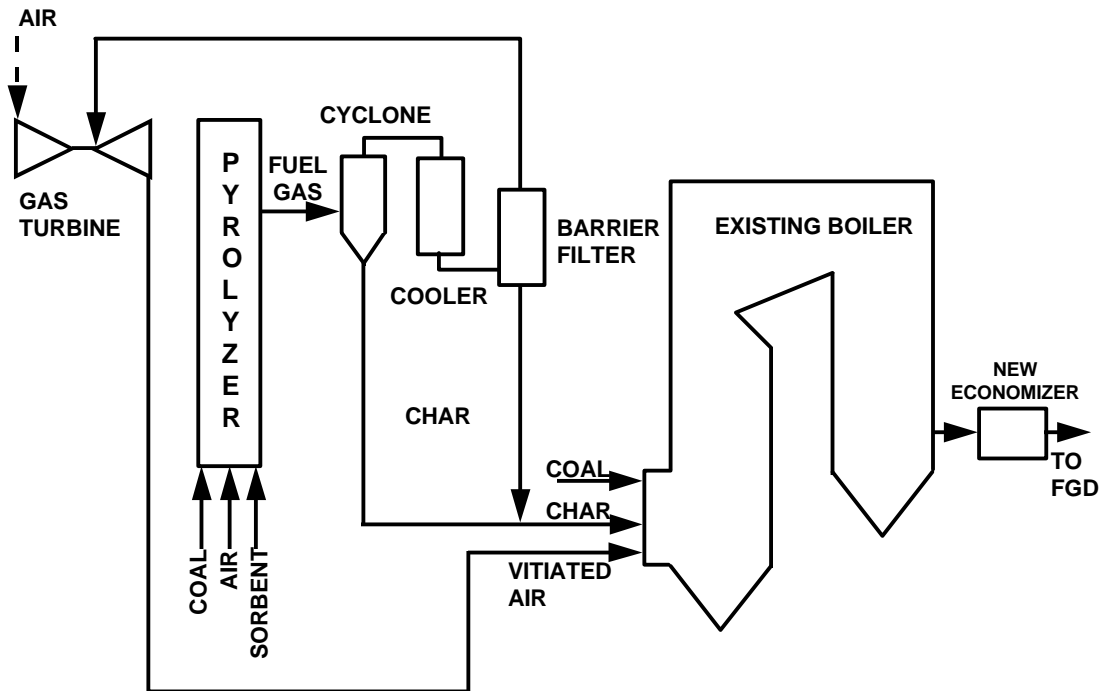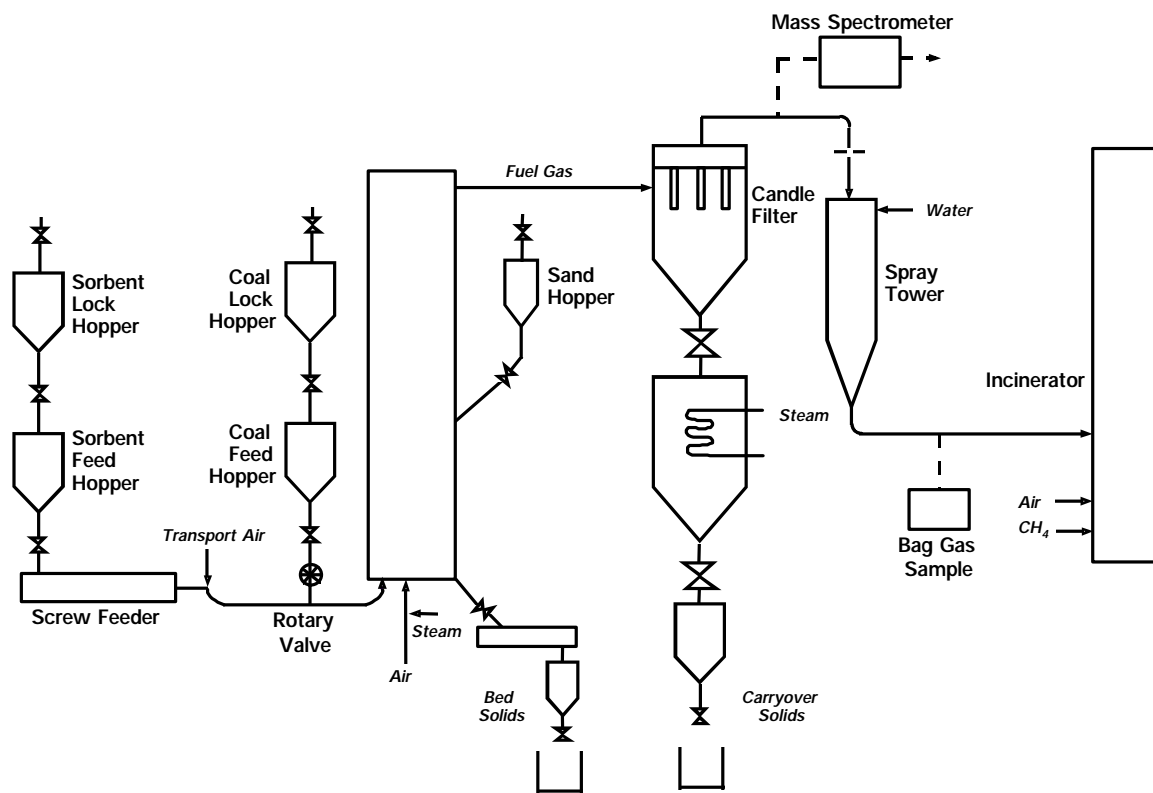

Figure 2. HIPPS Repowering Arrangement

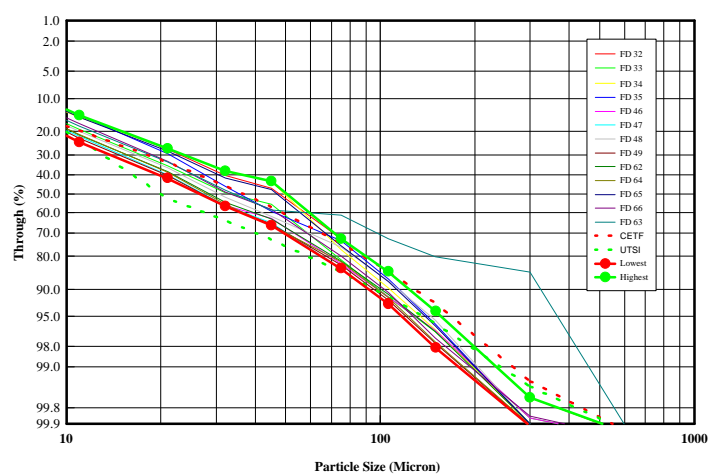Figure 3. HIPPS Pilot Plant Schematic and Sampling Locations

Figure 4. Typical Char Particle Size Distributions

Table 1. HIPPS Pilot Plant; Test Points Completed

Bed			Bed Temperature (°F)	Coal Flow (lb/h)	Steam Flow (lb steam/lb coal)	Ca/S
Sand	Longview Limestone	Pittsburgh No. 8				
Yes	1/8″ x 0	70% thru 200	1680	150	0	2.0
Yes	"	"	1680	130	0.17	2.0
Yes	"	"	1680	150	0.30	2.0
No	"	"	1800	400	0.2	1.2
No	"	"	1700	260	0	2.3
No	"	"	1630	300	0	1.0
No	"	"	1800	300	0	1.0
No	"	"	1700	300	0.2	1.0
No	"	"	1700	300	0.4	1.0

Table 2. Pyrolyzer Fuel Product Composition; Test Results vs Model Predictions

	Set Point #1		Set Point #2		Set Point #3	
	Results	Model	Results	Model	Results	Model
Fuel Gas Composition %						
N_2	69.74	68.97	62.52	64.80	62.29	61.48
O_2	0.00	0.00	0.00	0.00	0.00	0.00
CO	8.60	9.68	6.69	8.45	5.72	7.30
CO_2	8.15	8.38	10.83	9.62	10.88	10.63
H_2	6.30	6.79	8.50	8.52	8.30	9.49
H_2O	5.41	3.80	9.52	6.26	10.99	8.92
Ar	0.55	0.61	0.52	0.61	0.54	0.61
CH_4	1.05	1.54	1.18	1.51	1.08	1.33
C_2H_4	0.06	0.00	0.03	0.00	0.00	0.00
C_2H_6	0.00	0.00	0.00	0.00	0.00	0.00
H_2S	0.01	0.01	0.01	0.02	0.01	0.02
COS	0.00	0.00	0.00	0.00	0.00	0.00
NH3	0.12	0.28	0.19	0.29	0.18	0.28
	100.00	100.07	100.00	100.07	100.00	100.08
Elutriated Char Composition						
C	64.10	64.61	64.37	63.34	63.99	61.03
H	0.27	0.47	0.24	0.47	0.22	0.44
O	0.00	0.74	0.00	0.75	0.00	0.70
N	1.03	1.16	0.97	1.14	0.97	1.11
S	1.52	1.67	1.23	1.64	1.28	1.58
Ash	33.09	31.35	33.19	32.66	33.53	35.15
	100.00	100.00	100.00	100.00	100.00	100.00
Carbon Conversion % (Based on Gas)	49.48	50.79	56.46	53.69	55.99	58.54
Carbon Conversion % (Based on Solids)	53.47	50.79	53.49	53.69	54.39	58.54

Table 3. Summary of Bench-Scale Reactivity Tests

TEST	DIAGNOSTICS	PURPOSE
T_{15}	Measures temperature when sample has 15 ^{o}C/min rise	Ignition index. Harder to ignite fuels have higher T_{15}
TGA	Weight loss vs temperature at constant heating rate 20 ^{o}C/min	Relative fuel reactivity. Measures char ignition and burnout temperatures
Drop Tube	Char combustion efficiency and NOx emissions	Determines parameters at conditions similar to boiler; particle heating rate, excess air, residence time

Table 4. Summary of Reactivity Index and TGA Results

Fuel	Reactivity Index, ^{o}C	TGA Fuel T_{ig}, ^{o}C	Char Surface Area, m^2/gC	TGA Char T_{bo}, ^{o}C
Pitt # 8 char	429	475	163.8	650
Anthracite A	413	480	20.6	790
Anthracite B	519	580	11.8	860
Low Vol. Bit.	261	430	2.0	800

Table 5. Drop Tube Combustion Test Results for Different Fuels

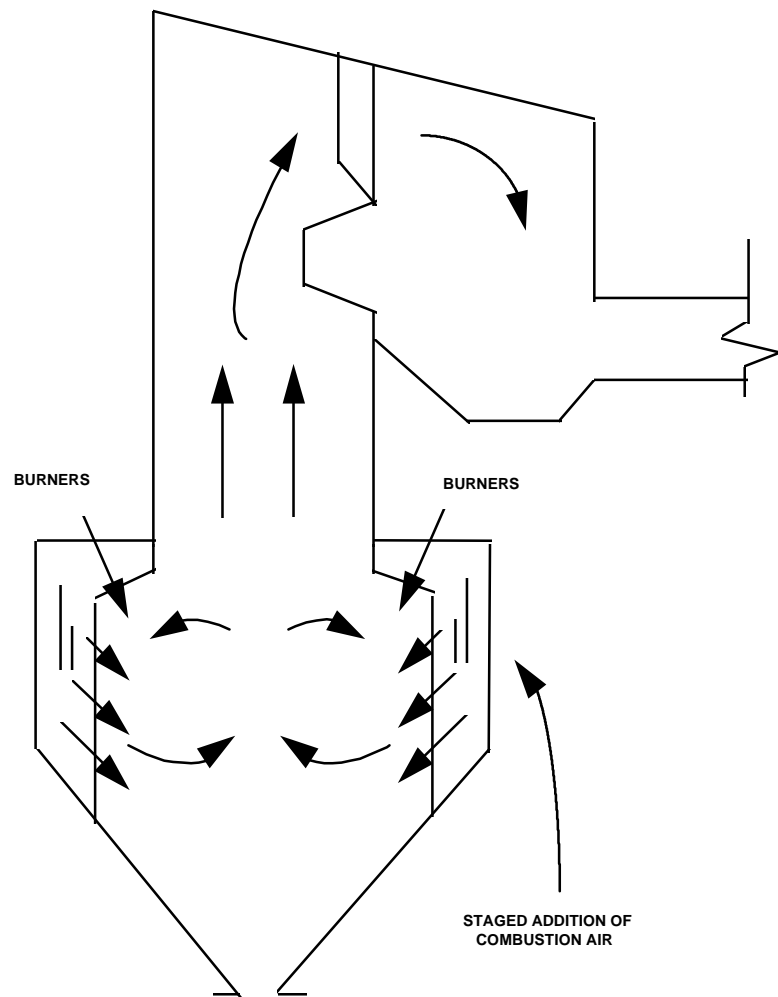| Fuel	Furnace Temperature, ^{o}C	Excess Air, %	Carbon Burnout, %
Pittsburgh No. 8 char	1500	25	97.4
	1500	25	97.4
		Avg.	97.4
Pittsburgh No. 8 char	1400	21	*
	1400	21	89.8
	1400	21	82.7
		Avg.	86.3
Anthracite A	1500	25	80.1
	1500	25	85.1
	1500	25	*
		Avg.	82.6
Anthracite A	1400	25	65.8
	1400	25	65.8
	1400	25	64.1
	1400	25	60.3
		Avg.	64.0
Anthracite B	1500	25	83.4
	1500	25	80.2
		Avg.	81.8
Low Vol. bituminous	1500	11	95.2
	1500	11	93.4
		11	93.4
		Avg.	94.0

BURNERS

BURNERS

**STAGED ADDITION OF
COMBUSTION AIR**

Figure 5. Arch-Fired Furnace